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THE ORIGIN OF THE EARTH

An NBC Radio Discussion by HARRISON BROWN
DIRK TER HAAR, GERARD KUIPER
and RUPERT WILDT

Including

THE ORIGIN OF THE EARTH
By THORNTON PAGE

RECENT THEORIES ABOUT THE ORIGIN OF THE SOLAR SYSTEM
By DIRK TER HAAR

NUMBER 598 * SEPTEMBER 4, 1949 * *10 cents*
Yearly subscription $3.00

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The University of Chicago ROUND TABLE. *Published weekly. 10 cents a copy; full-year subscription, 52 issues, three dollars. Published by the University of Chicago, Chicago 37, Illinois. Entered as second-class matter January 3, 1939, at the post office at Chicago, Illinois, under the Act of March 3, 1879.*

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The Origin of the Earth

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MR. BROWN: Few questions fire the imagination of men so much as the question of the origin of our own earth. Has this small sphere we call home, together with the other planets, always been? Were the planets at some time in remote antiquity formed as the result of natural processes which can be understood by men? If so, what can modern science tell us about those processes? What were the conditions which existed when the earth and the planets were formed?

Kuiper, you are an observational astronomer and have observed and studied the planets of our solar system for many years. Why do we talk about an "origin" for the solar system anyway?

MR. KUIPER: I think that you are quite right that we should clarify for our listeners the use of this term "origin." We do not propose to show that at one day in the remote past the solar system grew out of nothing. What we mean by using the term is that the present system of the earth and the other planets and the satellites grew out of an earlier, simpler form, very different in appearance from the present. We do not know all the facts as yet. The job of reconstruction is a difficult one.

MR. BROWN: Ter Haar, you are a physicist who has done a considerable amount of work on the question of the origin of the solar system. What would you say have been the primary changes in thought on this subject which have taken place during the past few years?

MR. TER HAAR: I would say that during the last ten years three different ways of attacking this problem have mainly been used. In England especially, Jeans's theory of a catastrophic origin, in which another star is thought to have passed the sun very closely and in this way brought a gaseous mass out of the sun which consequently developed into the planets, has been developed further. In Sweden, the influence of the sun's magnetic field has been studied. But probably the most promising of all the developments has been von Weizsäcker's theory, which was published in 1944, during the war.

MR. BROWN: Wildt, you are an astrophysicist who has given considerable thought to the composition and structure of the planets. Do you have anything to add to this statement which ter Haar has made?

MR. WILDT: I have indeed. I should like to suggest that theories of the origin of the earth now must pass more severe tests than those employed previously. It has been only in the last ten or fifteen years that we have obtained fairly precise information on the physical and chemical constitution of the other planets. Though at first sight it might seem that the problem has become more difficult because there are new features of the planetary system which call for explanation, perhaps these are data which lighten our task in the end, for they might help us to come to a decision among rival theories.

MR. BROWN: It seems to me that studies in the origin of the solar system constitute a very rapidly growing science. I think that, in order to get started in our discussion here, we should ask ourselves, how do we know that the earth has not always existed? How do we know that we have to have an "origin" in the strict sense of the word? Kuiper, how long would you say that the crust of the earth has been solid, for example?

MR. KUIPER: I think that we have to rely here on the results of geologists' studies. Geologists find it possible to determine the age of rocks by studying the content of uranium and thorium in the crust of the earth and the decayed products of those elements. This radioactive decay cannot be hastened or slowed up by heat or by pressure or other physical forces and for this reason is a reliable measure of time. The solid body of the earth, which must have existed, by these radioactive tests, about two billion years in approximately its present condition had been preceded by an earlier state, we assume, in which the outer parts of the earth were molten.

MR. BROWN: Then you would say that the earth is at least two billion years old, is that correct?

MR. KUIPER: That is the best information geologists provide us.

MR. BROWN: Wildt, do you have anything to add to that? Do we know anything concerning the previous history of the earth, the previous physical condition of the earth?

MR. WILDT: The way I see it, we seem to have a choice between two mental pictures of the origin of the earth. Either it began its existence as a separate body in a cataclysm and gots its start as an intensely hot body which rapidly cooled down and before long acquired a solid crust (Jeffreys has computed that this process could not have taken more than ten thousand years); or the earth grew gradually, nearly as a snowball

grows. That is to say, it began as a small cold body, rolling through space and gathering dust by virtue of its gravitational pull. It finally stopped growing when the cloud of gas and dust from which it fed became exhausted. If we prefer the second picture, we must find an answer to the question, how did the earth's interior get as hot as it is now? But more about that later.

MR. BROWN: Then, as you see it, Wildt, the earth consists of a body which at one time was very hot to the point of being molten. It was in this state, say, roughly two billion years ago. Ter Haar, how did the earth get into that condition anyway? How did the earth come to grow into a separate body?

MR. TER HAAR: If you are inclined to accept the ideas of von Weizsäcker, that is, if you are inclined to accept the idea that our whole solar system grew out of some gaseous mass, then it is not so difficult to see how a mass, a body like our earth, could have been formed. Just as, if one has a supersaturated water vapor, out of this water vapor there will be formed little drops of water. Finally, if there is enough water vapor present, a whole space can be filled with water. In the same way, it is possible that in a cloud such as von Weizsäcker pictures there was a condensation into little crystals and that those little crystals will, in the way Wildt just pictured, grow and grow until they finally become as large as the earth is at present. I think that that is, roughly, the picture which I would like to accept for the growth of the earth.

MR. BROWN: Gentlemen, we have been confining our discussion thus far to the earth. As you, Kuiper, pointed out, we can measure the age of the earth directly. In the case of the other planets we cannot get our hands on them, so to speak, so we cannot measure their ages. Do we have any evidence at all that the other planets are the same age as the earth?

MR. KUIPER: We have no accurate data on the ages of the other planets, because we cannot go there and repeat the tests which geologists have used on the earth. However, we can derive conclusions about the age of the solar system as a whole. For instance, the orbit of Neptune would have been disturbed by passing stars had the solar system been extremely ancient. Similarly, it is possible to make some guesses as to the age of the sun. We know that the sun is dissipating its energy at a great rate and therefore cannot have been doing so for a very, very long time. The conclusion is that the data we have on the sun and on the other planets are consistent with the age determination of the earth as made by geologists.

MR. BROWN: As I see it, then, we have the following picture—that of a solar system coming into existence approximately two or three billion years ago in some manner which as yet we do not completely understand. Kuiper, as an observational astronomer, what would you say are the main observed facts which any theory of the origin of the solar system must explain?

MR. KUIPER: I think that it is best to look at the inventory of the solar system. Everyone knows that we have nine major planets in the solar system. There are also some hundred thousand small planets, ranging in sizes from about five hundred miles in diameter to diameters less than one mile. There are billions of meteorites, thousands of comets, and at present thirty known satellites. In other words, we have a very vast family of objects in the solar system. The remarkable fact is that the planets, large and small, move essentially in a flat disk, as if they were attached to some plane like a table. Furthermore, all of them move around the sun in the same direction. Finally, we can point out that the composition of the atmospheres of the planets bears a strong resemblance to the composition of the earth's atmosphere and can be understood as having been derived from essentially the same sort of material as we find in the sun and between the stars.

MR. BROWN: What do you mean when you say that the atmospheres of the other planets bear a resemblance to the atmosphere of the earth?

MR. KUIPER: For instance, on Venus there is a great deal of carbon dioxide, which is a prominent constituent of our own atmosphere. On the outer planets there is much methane and ammonia. Now we do not have large quantities of methane and ammonia present here on earth, but that is because the earth has very little hydrogen, a fact which, again, can be understood in terms of modern physics.

If we assume in the theory material very similar in composition to that of the sun, the conclusion is that, at the temperatures at which those various planets exist, substances would have formed just as we actually observe them in our telescopes and spectrographs. So the picture of the composition of the planets is consistent with uniform composition of the original solar nebula out of which those planets formed.

MR. BROWN: Apparently there are a number of regularities in the solar system which must be explained concerning the mechanics of the motions of the planets and certain regularities concerning the atmospheres of those planets. But what about the interiors of these planets? Wildt, you

have given a great deal of thought to that question. What sort of regularities might exist there?

MR. WILDT: The difficulty is, of course, that we cannot look into the interior of the planets. In the case of the earth we have some information resulting from geophysical investigations. We know, for instance, that heat is flowing out from the interior of the earth. Consequently, the temperature there must be much higher than at the surface. Secondly, the pressure must greatly increase toward the center of the earth, on account of the weight of the overlying material.

MR. BROWN: What is the pressure in the center of our own earth, Wildt?

MR. WILDT: Oh, I would say that it is about several million atmospheres at least.

MR. BROWN: That would mean that in the case of Jupiter the pressure is really almost unbelievably high.

MR. WILDT: In the case of Jupiter, on account of the higher mass, the pressure must be at least ten times as large as it is at the center of the earth. Now, in the case of Jupiter we have to expect an internal constitution quite different from that of the earth. Strange to say, the planets Jupiter and Saturn are extremely light bodies.

MR. BROWN: You mean light in this case, Wildt, in the sense of density, do you not?

MR. WILDT: Yes, they are light in the sense of density. Saturn is a body lighter than water. It would float on water. The earth is an extremely dense body. The density of the entire earth is about twice that of the rocks which we observe at the surface of the earth. We must conclude, therefore, that it has an extremely dense core in the center.

MR. BROWN: Ter Haar, we have had a vivid picture from Wildt and from Kuiper concerning the observations on our own solar system. It seems to me that when we look through textbooks and popular discussions on the question of the origin of the solar system we find cropping up again and again a theory which states that another star came by our sun and pulled off a glob of matter in some way. Then, according to that theory, that glob of matter condensed into our present solar system, including the earth. How do you feel about that theory?

MR. TER HAAR: I am afraid that that theory, which indeed was very

popular not so very long ago, is completely unsatisfactory. You see, if another star really had pulled a lot of gas out of the sun, it can easily be shown that the tidal forces from both the sun and the other star acting on this material, and also the pressure itself inside this gas would be so large that the gas would fly away and would dissipate into the universe before anything else could happen. I really do not think that this theory can stand any serious criticism.

MR. KUIPER: So I understand you to say, then, that this filament which, according to the previous theory, was pulled out of the sun would not be able to condense at all but would instead dissipate—spread out in space—and that no condensation into planets could ever occur.

MR. TER HAAR: That is right. I certainly would say that.

MR. BROWN: If we discount that theory, we must then search around for some other explanation. Ter Haar, out of this wealth of material which Kuiper and Wildt gave us, what would you consider to be the basic facts, the most important facts, which must be kept in mind if we are going to secure an explanation of the origin of the solar system?

MR. TER HAAR: I think that both Kuiper and Wildt already pointed these facts out very clearly. The first fact which must be explained is that all the planets are moving in the same plane, or, as Kuiper put it, are moving as if they were on a table, and they are all moving in the same direction about the sun. The second fact to be explained is the one which Wildt pointed out, that there is a big difference between the terrestrial planets which are close to the sun and which have a great density and the giant planets which are much farther away from the sun and which have such low densities that they would almost float on water. I should say that these two points are the most important ones to be explained by any acceptable theory.

MR. BROWN: On what basis do you think that one can explain these facts?

MR. TER HAAR: I am inclined to believe that the picture which the German philosopher Kant first drew in 1755 and which was developed recently by von Weizsäcker is probably the most acceptable. In that theory we have a large, rotating, gaseous envelope around the sun. I think that it is safe to assume that this solar envelope had about the same composition as that which the sun or the material between the stars has at present. I think, Brown, you might agree with me there.

MR. BROWN: Yes, hydrogen is by all odds the most abundant element in the sun and in the stars, and it would appear that this gas which surrounded the sun in envelope form at that time was also composed primarily of hydrogen.

MR. TER HAAR: You see, if we accept that idea, then we see the further fact that this gaseous envelope, rotating around the sun, will develop into a kind of disk or pancake. That, of course, is the original pancake from which the pancake of the planetary orbits, which Kuiper just mentioned, would develop.

MR. BROWN: You would visualize this pancake as extending out to the orbit of Pluto, would you not?

MR. TER HAAR: Yes, and, you see, this pancake has also the characteristic that the temperature in the pancake will decrease very much from regions near the sun to regions farther out.

MR. BROWN: In the same way, due to the fact that the temperature decreases going outward, I imagine that the density will probably reach a maximum at some place in between, would it not?

MR. TER HAAR: That is right. The density will probably have been at a maximum somewhere in between—say, in the region where the earth is at present.

MR. BROWN: I see.

MR. TER HAAR: In this disk there will be the same process which I described a moment ago in discussing the growth of the earth. There will be condensation into little crystals. Also, due to the fact that the temperature near the sun is different from the temperature farther out, there will be different kinds of crystals near the sun than in the outer regions. Near the sun there will be all kinds of metal crystals, while farther out the crystals will be of a more rocky nature.

MR. BROWN: That is entirely due to the differences in temperatures between the two locations?

MR. TER HAAR: That is right.

MR. KUIPER: Would you say, ter Haar, just to clarify this somewhat unusual picture, that one might compare these crystals with meteorites, the small shooting stars which hit the earth every day in so many millions?

MR. TER HAAR: Yes, I think that that is not too bad a picture.

MR. BROWN: But during the initial stages of this condensation the particles were probably very much smaller than the average meteorite which strikes the earth today, were they not?

MR. TER HAAR: Oh, that is certainly correct.

MR. BROWN: As a matter of fact, how large will these crystals be? They will be just small specks of dust, will they not?

MR. TER HAAR: They will start out as extremely small specks of dust or as little raindrops or whatever you want to visualize.

But there is one more element in this picture. Since the metal crystals will finally build up the terrestrial planets and since we know that metals are heavier than rocky materials, we should really expect that planets near the sun should have a larger density than the planets farther out.

MR. BROWN: This material from which the terrestrial planets were formed, then, would be an exceedingly small fraction of the total amount of gas present in the original pancake, I should imagine. Is that not correct?

MR. TER HAAR: Yes, I should guess that about only 1 per cent of the total gas present in this gaseous disk would condense finally.

MR. KUIPER: All the hydrogen, which was by far the most abundant element around in this area, must have escaped out of the solar system before we got into the present condition.

MR. TER HAAR: Oh, yes, that is certainly true.

MR. BROWN: Once this condensation process has taken place, then what happens, according to your views?

MR. TER HAAR: Those crystals will grow and grow until they finally get as large as the earth. When they get as large as the earth, they will capture some more gas, and they will go on until finally all the gas has been used up and there is no gas left. Of course, then they cannot grow any longer.

MR. BROWN: Ter Haar, as I understand your picture, the outer planets should be formed of material in addition to the stuff from which the inner planets are made, namely, water and perhaps methane and ammonia and perhaps hydrogen and helium. Wildt, from the looks of things, that fits in pretty well with your picture of the internal constitution of these outer planets, does it not?

MR. WILDT: Indeed, I am quite attracted by the process ter Haar has suggested, because it seems to give a satisfactory explanation of why these lighter planets have formed at a greater distance from the sun. The one point about which we cannot be certain at present is the existence or absence of heavy cores in these giant planets. It is quite possible that when we learn more about the compressibility of helium and hydrogen under high pressure, we shall find out that we could envision a planet of the size of Jupiter or Saturn composed of hydrogen alone. Thus, in these big planets, cores may be absent altogether. At any rate, the existence of small cores is not ruled out in the von Weizsäcker theory. So I would say that the new theory has a distinct advantage of offering us an explanation both of the mechanical and of the principal chemical features of the planetary system.

MR. KUIPER: We have not said very much about the satellite systems, which are, so to speak, miniature solar systems. A number of satellites have been found around Jupiter, and quite a number around Saturn. Uranus has five, and Neptune has a couple. Can one explain the origin of these minor bodies around the planets in a fashion similar to the von Weizsäcker theory, ter Haar?

MR. TER HAAR: Yes, certainly so. As I just said, larger planets really can get around themselves quite extensive atmospheres. In these atmospheres there may be a condensation process just like the one which occurred in the envelope around the sun. This would give rise to a satellite system, just as the condensation process in the gaseous disk around the sun gave rise to the planetary system.

MR. BROWN: It appears that we have, then, a theory which goes considerably beyond our older concepts of the origin of the solar system. I think that you will probably agree that there is very much still to be explained. But I would like to know, Kuiper, in your view, how this general view which ter Haar has presented fits into our broader cosmological picture.

MR. KUIPER: I think that the theory which we have heard described by ter Haar, and to which he himself has made such valuable contributions, is but a part of a wider theory which describes the origin of stars, of spiral nebulae, and, in fact, the development of the whole material universe. The modern theory uses the latest results on turbulence and is related to studies with wind tunnels and to eddies in rivers. We are deal-

ing here with a hierarchy of whirlpools of gas: large ones leading to galaxies, smaller ones leading to stars and planetary systems, and still smaller ones to satellite systems. The smaller whirls which we might expect in the big ones lead to condensation, and the planets are formed.[1]

Finally, I would like to comment on a question which is very often asked, are there planetary systems other than our own? The best answer which astronomers can give is "Yes." Probably about one star in a thousand is attended by planets, and, since there are some one hundred billion stars in our galaxy, this would make about one hundred million planetary systems in our galaxy alone. As you know, there are many hundreds of millions of galaxies which can be observed with large telescopes. However, all planetary systems except our own are too faint to be observed.

MR. BROWN: Kuiper, that last result in itself shows that, during the last decade or so, breath-taking results have taken place concerning the origin of our solar system. I think that we can expect that during the next decade equally rapid progress will be made. Because of that, I think that it is important that from time to time we should reopen this subject for further discussion.

1 See *The History of Nature* (Chicago: University of Chicago Press, 1949), by C. F. von Weizsäcker, the originator of the nebular theory of the evolution of the solar system discussed in this ROUND TABLE. The book considers the philosophic background and scientific importance of the new theory.

THE ORIGIN OF THE EARTH*

By THORNTON PAGE
University of Chicago

WITH all the spectacular success of recent scientific research, it is perhaps refreshing to examine a field so characterized by failure as this one. Although many speculations have been described as "theories," there exists today no real theory of the origin of the earth in the sense of a complete logical structure linking together the vast quantity of pertinent observations collected during the last century.

The most obvious approach to the problem is to study the visible surface of the earth for clues as to its origin. This has been done in detail by geologists, geophysicists, and geochemists, but it is perhaps not surprising that what they find has more to do with the earth than with its origin. It has been the astronomer, studying the relation of the earth to its surroundings, and the physicist, studying the behavior of matter, who have made the greatest progress in the study of the earth's origin.

Early speculation on the subject was simple and direct because there were fewer observations to explain. The assumption of a divine creation of things as they are was generally accepted until the end of the sixteenth century. Then the revolution in scientific thinking, started by Galileo, turned men from assumptions of a catastrophic origin to a belief in natural development, understandable in terms of what can be seen and measured today. As the astronomical picture became clearer, it appeared that the earth is a relatively small, nearly spherical body moving around the sun together with the other planets, all under the influence of the sun's gravitational attraction. It was soon recognized as scarcely due to chance that all the known planets and their satellites are moving and rotating in the same direction, their orbits nearly circular, and in nearly the same plane. Therefore, in 1755, the great German philosopher-scientist, Immanuel Kant, speculated that the planets and the sun were formed from a single large rotating gaseous cloud, or nebula, which had condensed into smaller rotating parts, these further condensing into rotating planets with their satellites, all moving in the same direction around the nucleus of the nebula which became the sun. Kant's hypothe-

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sis explained nearly all the available observational data within the framework of physics as it was developed at the time.

Later on, about 1800, the French mathematician, Laplace, independently proposed a modified form of the Kant hypothesis, which, even though it was not given much weight by its author, soon became widely accepted as the concept upon which much of geology was founded. Laplace went further than Kant in explaining how the primordial nebula condensed into planets. He assumed that in the beginning the nebula was hot and spinning slowly, that the gas contracted as it cooled and therefore increased its spin in accordance with the law of the conservation of angular momentum. As the spin increased, he reasoned, rings of gas would be thrown off by centrifugal action and each ring would condense into a planet. It is now recognized that no such condensation of hot gas at the rim of a spinning nebula would take place, but Laplace's speculation was important in that he introduced two new factors: the idea that the earth condensed from hot gases, and the consideration of angular momentum in the solar system.

Not until 1895 was the Laplace hypothesis seriously challenged. By that date geology had come into its own as a science, and T. C. Chamberlin, an American geologist, considered the geological evidence incompatible with the concept of a hot gaseous sphere, cooling to become the present earth. Instead he proposed the planetesimal hypothesis, in which the earth and other planets were built by accretion of cold particles (the planetesimals) which were moving around the sun under its gravitational attraction. Together with an astronomer, F. R. Moulton, he suggested that such planetesimals might have resulted from a near-collision between another star and our sun. The planetesimal hypothesis introduced two new concepts: that the earth was built by accretion of cold solid material, and that another star was involved in forming the solar system. The near-collision presumably being a rare event, this represented a return, in part, to the old concept of a catastrophic origin.

During the last fifty years, most of the thinking on this problem has been divided between the two widely divergent hypotheses of Laplace and Chamberlin. Did the earth start hotter or colder than at present? Has it condensed and contracted, or grown by accretion? Was its origin a commonplace occurrence in a nebula, (many of which can be seen in the sky), or due to a highly unusual near-collision between stars? Whatever drawbacks these incomplete speculations may have had, they have

KANT—1755

Clotting mass of gas and dust in rotation.

Clots grow by accretion to form planets and satellites. Remainder of nebula contracts to form sun.

provided definite concepts on the basis of which further research has been and yet remains to be done. . . .

The Record in the Rocks

The best geological evidence, summarized, is that the earth is at least three billion years old and its surface conditions of temperature and atmosphere have not changed materially in one billion years and not radically in three billion years. Its stratified layers from density about three at the surface to density about thirteen at the center could result from plastic flow and chemical compaction whether or not the earth were originally molten. Finally, the earth lost most of its gases early in life. . . .

Shooting Stars

An important bridge between geology and astronomy is provided by the meteors. Millions of these small chunks of rock and iron collide with the earth each day, most of them burning up high in the atmosphere. Some of the larger, slower moving ones reach the ground; there the few collected are the only material from outside the earth available for detailed study. Are they a few remaining planetesimals—or are they visitors from outside the solar system?

Measures of meteor speeds by Whipple at Harvard have established that they are at least members of the solar system. If they came from outside they would be moving much faster than observed. Radioactivity measurements (as in dating rocks, but corrected for the effect of cosmic rays which form extra helium) show that the meteors are between two and three billion years old, in startling agreement with the earth's age. Their high iron and nickel content has supported the assumption that the earth's core is nickel-iron (so that the earth and meteors would have the same all-over composition).

Furthermore, Harrison Brown's recent studies of the chemicals present in meteorites show that they were probably at one time under the high pressures and temperatures of a planet's interior. It would seem that, far from being planetesimals, the meteors are the remains of a fair-sized planet which was formed at the same time as the earth, and which broke up in some large-scale interplanetary collision at a later date.

The Gamut of Speculation

The astronomer, in his approach to the problem of the earth's origin, started by recognizing a certain order and regularity among the planets, their satellites, and the smaller asteroids, all moving about the sun. The

LAPLACE—1796

Rotating nebula (hot gas).

Cooling nebula shrinks, spins faster, and is expected to leave rings of gas to condense into planets. Whole remainder forms sun.

emphasis is shifted from the origin of the earth, as one of the planets, to the origin of the solar system as a whole. The latest trend goes even further in linking the origin of the solar system with the early history or origin of our galaxy of stars and even of the whole universe.

The solar system regularities noted by Kant clearly indicate that the planets had a common origin; ever since Kant's time it has been the fond hope of cosmogonists to establish the exact nature of that origin from further studies of the over-all pattern of the solar system. The first clue of this sort to be noticed was the spacing of the planets; they are not at irregular distances from the sun, but spaced approximately in geometric progression—that is, the distances can be calculated roughly from a formula called Bode's law after its discoverer. Since the planets continue to move in the same orbits year after year, this spacing must have been established during their formation.

A second possible clue to the origin lies in the progression of planet sizes—from the smallest, Mercury, which is nearest the sun, increasing through Venus, Earth, and Mars to Jupiter, the largest, then decreasing through Saturn, Uranus, and Neptune to Pluto, a small planet, and most distant from the sun.

Further clues will be noted as we follow, now, the twentieth century history of speculation on the birth of the solar system, from Chamberlin to Weizsäcker.... Each of these theoreticians has started either from the Kant nebular hypothesis, or from the Chamberlin two-star hypothesis, and tried to show by more or less exact reasoning that the presently observed solar system would have resulted naturally. Chamberlin and Moulton in 1900 guessed that the close approach of any other star to our sun would raise great eruptions on the sun, that hot solar materials would condense into small planetesimals moving around the sun and that these planetesimals would later stick together to form the planets by accretion.

In 1917 the English astronomers Jeans and Jeffreys made more exact calculations and concluded that the eruptions would not have taken place; rather, the intruding star would have to sideswipe the sun, peeling off a long filament of solar material which would then condense into the planets. They pointed out that this filament would be thicker in the middle than at the ends, thereby accounting for the progression of planetary sizes.

The Jeans-Jeffreys hypothesis seemed satisfactory until 1930, when Nölke in Germany and Russell at Princeton pointed out another clue:

CHAMBERLIN–MOULTON–1900

A passing star narrowly misses the sun. Huge eruptions are expected to occur on both as they pass.

The sun is left with a vast number of planetesimals which condensed from the erupted gases and slowly coagulate to form planets. The intruding star should also have planets forming.

the angular momentum of the planets. Just as a spinning top would keep on spinning forever if there were no friction, so the planets must have maintained constant angular momentum in their orbits around the sun, since nothing analogous to friction is known in the solar system. If the planets were formed of material pulled out of the sun, this law of conservation of angular momentum requires that the original planetary material must have started moving around the sun with the same angular momentum the planets have today. Russell showed mathematically that a grazing collision with another star could not start the filament of planetary material off with anywhere near enough angular momentum.

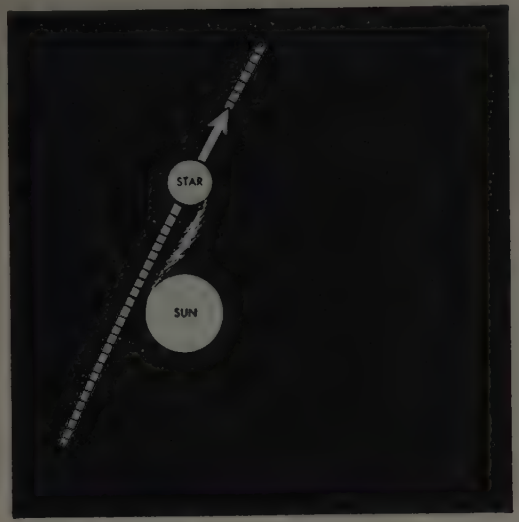
In an effort to patch things up, one of Russell's students, Lyttleton, analyzed mathematically the case of a collision between three stars, and found that it was just possible to produce a filament of material moving with sufficient angular momentum about one of them. An English astronomer, Hoyle, showed it was also possible if one of two close stars blew up, as a somewhat asymetrical nova, propelling itself away and leaving some planetary material moving around the other star.

But these mathematical exercises and the whole sequence of speculations based on the two-star hypothesis were brought sharply to a close in 1939, when Spitzer, another of Russell's students, calculated that the material pulled out of the sun, or any other star, could not condense into planets or planetesimals anyway—it would expand with explosive violence to form a tenuous gaseous nebula!

Back to the Nebular Hypothesis

Long before Spitzer had showed that the two-star hypothesis would lead to a nebula, other scientists had been working away on the nebular hypothesis, trying to find some means by which material near the sun would form a group of planets all moving in the same direction in nearly circular orbits and in nearly the same plane. In 1914 a Norwegian physicist, Birkeland, calculated that electrically charged particles shot out of the sun would spiral out in the sun's magnetic field to definite circular orbits at distances depending on the electric charge and the mass of the particles. This promising lead was followed further in 1930 by a Dutch meteorologist, Berlage, who assumed the particles were charged atoms. More recently, in 1942, the Swedish physicist, Alfvén, was able to predict by similar reasoning that rings of gas with sufficient angular momentum would be formed around the sun as the sun moved through a nebula, but

JEANS–JEFFREYS–1917



A passing star sideswipes the sun, tearing out a long filament of gaseous material.

The gas is expected to cool and condense into planets, the largest one in the middle and smaller ones at either end.

both he and Berlage have avoided the embarrassing problem of how this gas could condense to form planets.

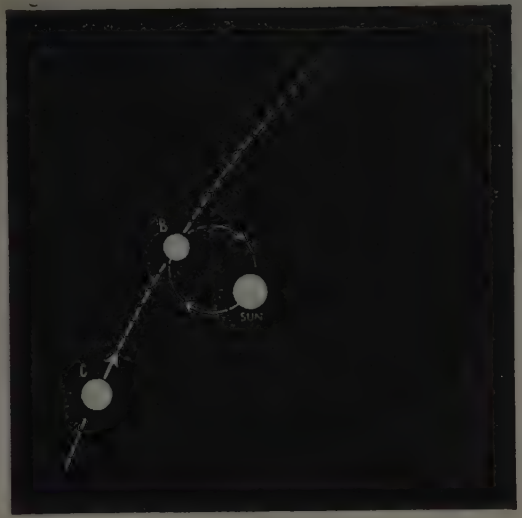
Lastly in the sequence of nebular speculations, a German physicist, Weizsäcker, has recently investigated in detail the motion of a large cloud of dust and gas in rotation about a massive central body like the sun. From this return to the ungarnished Kant hypothesis he was able to show that, while most of the gas would escape into outer space, the planets could be formed by the accretion of the dust particles over a period of a hundred million years—a short time compared to the age of the earth. The spacing of the planetary orbits Weizsäcker explains in this manner: The inner parts of the rotating nebula would be pulled around more rapidly by the sun's gravitational attraction than the outer parts. Like stirring a bowl of soup near the center, this would set up eddies, and at the boundaries of the eddies, the dust would coagulate most rapidly. These boundaries, Weizsäcker calculated, would be spaced approximately in a geometric progression from the sun just as the planets are observed to be.

The Weizsäcker hypothesis accounts for more of the observational data than any of the previous speculations, but because it is so recent a number of its consequences have not been explored and some of the estimates may need revision.

One of the interesting consequences is that the formation of planets should be an extremely common occurrence. Possibly in the process of formation of *every* star the conditions would be correct to form planets. Thus we might expect billions, if not hundreds of billions of planets in our galaxy, the strong likelihood that life has developed on a million or more of these, the high probability that there are other civilizations of mankind, and even the possibility that men on other planets are writing articles on the origins of their solar systems! . . .

In an echo of the introductory remarks it scarcely needs to be emphasized that we have no complete theory of the origin of the earth. The reader may be impressed with the diverse investigations involved and with the promise of the latest speculation; or he may notice the infinite regression implicit in any question of origins; if the planets were formed from dust or planetesimals, whence came the dust or planetesimals? if the dust and planetesimals came from a primordial nebula, whence came the primordial nebula? and so on, *ad infinitum*.

LYTTLETON—1936



If the sun originally had a close companion, B, spinning around it, a third star, C, might have sideswiped the companion . . .

. . . carrying it away, and leaving a filament of its gas moving around the sun, with lots of angular momentum.

RECENT THEORIES ABOUT THE ORIGIN OF THE SOLAR SYSTEM*

By D. TER HAAR

Department of Physics, Purdue University

MANY theories concerning the origin of the solar system, starting from a plausible, hypothetical, original situation, have been offered since Descartes, in 1644, made the first attempt to explain the observed regularities of our planetary system.

In the last decade, renewed interest has been shown in this subject, and new theories have been proposed by physicists and astronomers. Before considering these theories in detail, let us summarize briefly those features of the solar system which require explanation. As was long ago pointed out by Laplace, there are so many regularities that the system could not have been formed fortuitously but must be genetically related. This is sufficiently established by the fact that the revolutions of all the planets and asteroids about the sun are in the same direction.

Regularities of the Solar System

The solar system consists of the sun, nine large planets, twenty-eight satellites revolving about six of these planets, more than fifteen hundred asteroids, and the comets and meteors. Our main concern here will be with the planets.

The regularities shown by the planets may be divided into four main groups:

First, there are the orbital regularities. Apart from the common direction of orbital motion, the eccentricities of the orbits are small, and the orbital planes are practically the same. The rotation of the sun is also in the same direction, and its equator is only slightly inclined to the planetary orbital planes.

Secondly, the mean distances of the planets from the sun obey very closely the so-called Titius-Bode law. This law gives, as the expression for the mean distance of the nth planet from the sun, $r_n = a + b \cdot 2^n$, where $a = 0.4$ A.U. and $b = 0.3$ A.U.[1] and where the group of the asteroids is counted as one of the planets.

The law $r_n = r_0 \epsilon^n$ instead of the Titius-Bode law gives us, with about

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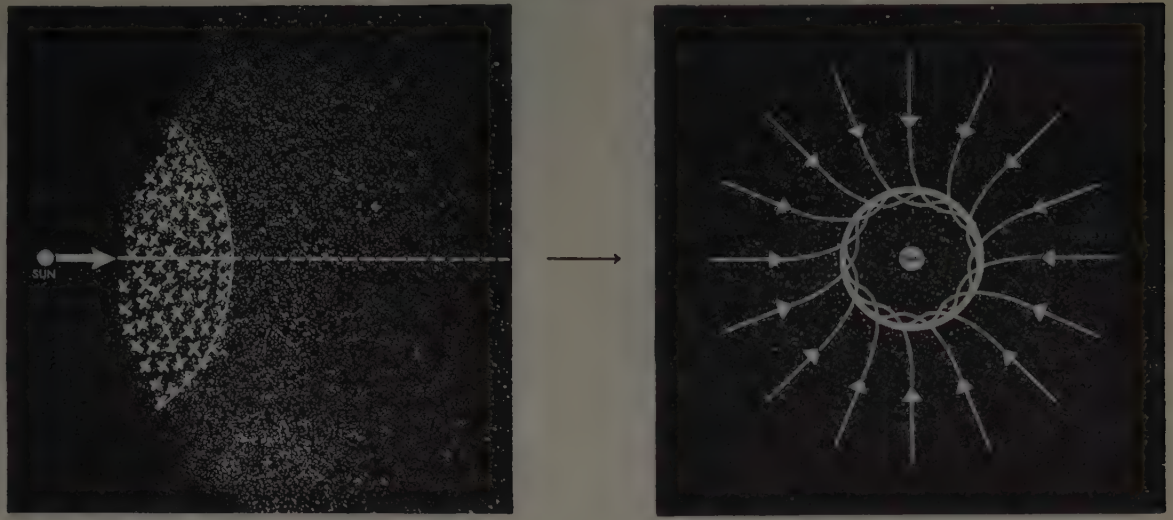
[1] One A.U. (astronomical unit) = mean distance of the earth from the sun.

ALFVEN—1942



The sun, rushing through space at twelve miles per second, passes through a gaseous nebula. Its presence creates electric charges on the atoms of gas.

The charged atoms spiral inward to form rings of gas (only one is shown here) which might later condense into planets.

the same amount of accuracy, the mean distances of the planets from the sun. This expression is often more convenient to use, and, when we refer to the Titius-Bode law, we will have in mind this expression.

For the satellite systems of Jupiter, Saturn, and Uranus laws such as that given in the above equation apply (with different ϵ's). Also, the orbits of these satellites show the same regularities as do the planetary orbits.

Altogether, the satellite systems are analogous to the planetary system in so many ways that the conclusion seems unavoidable that the manner of their formation should essentially have been the same.

The third feature of the solar system which requires explanation is that the inner, or terrestrial, planets (Mercury, Venus, the earth, Mars) and the outer, or major, planets (Jupiter, Saturn, Uranus, Neptune) are separated not only in space but also by their physical properties. The inner planets are comparatively small bodies with a high specific density, low rotational velocity, and few satellites. The outer planets, on the other hand, are large, their specific density low, their rotation fast, and their satellite systems extensive.

The fourth and last feature of the solar system which has to be explained is the distribution of the angular momentum. The sun possesses about 99 per cent of the mass of the total solar system, but only 2 per cent of the total angular momentum. Failure to explain this point has caused the downfall of many theories in the past, the most notable being those of Kant and Laplace.

We may indicate here, briefly, the difficulties, first pointed out in 1884 by Fouché, inherent to the distribution of the angular momentum. The angular velocities of the planets are determined by their mean distances from the sun in accordance with Kepler's laws. The strange thing is not that the planets have such a large angular momentum but that the sun rotates so slowly.

If one attempts to account for the origin of the solar system by some kind of catastrophe, this accident may have brought about the present distribution of the angular momentum. If, however, one tries to develop a theory starting from the sun alone, perhaps surrounded by a gas cloud, it is not easy to see how the average angular momentum per unit mass should be so much lower for the solar than for the planetary matter.

Of course, the four main groups of regular features mentioned above are not the only ones exhibited by the solar system. We will not discuss here the other properties of the solar system, such as the Saturnian rings

or the asteroid system. Some of these irregularities can be explained easily, while others still await an acceptable explanation.

Prior to a discussion of some of the new theories proposed during the last ten years, it should be pointed out that all theories about the origin of the solar system can be divided into two groups, according to whether or not they assume an interaction with other celestial bodies as an integral part of the development of the solar system. In the first case, we have an open system; these theories are called *dualistic* or *catastrophic*. In the second case, the system is closed, and the theories are called *monistic* or *uniformitarian*.

For a critical survey of older theories, the reader is referred to the many excellent textbooks written on the subject. Here the discussion will be confined to the recent dualistic theories of Lyttleton and Hoyle and the recent monistic theories of Alfvén, Whipple, Berlage, von Weizsäcker, and ter Haar.

Binary Theories

Russell pointed out that the tidal theories of Jeans and Jeffreys are unable to explain the distribution of the angular momentum, although, at first sight, the encounter of a second star with the sun seems to be able to provide the system with sufficient angular momentum. Russell himself suggested as a possible, though not very promising, way out that the sun might have been a binary star whose second component was removed by some kind of a catastrophe.

Lyttleton has followed up this idea and given two different theories along those lines. The first one followed Russell's idea very closely and assumed that a third star collided with the sun's companion. In that way, the binary system may have been broken up and a gaseous filament provided which would thereafter condense into the planets in a way analogous to the condensation in the tidal theories. Although it seems that Luyten's criticism is not valid, there are still too many difficulties connected with this theory for it to be accepted as a final solution, *e.g.* we may mention here Lyttleton's own difficulty in accounting for the satellite systems.

The alternative solution suggested by Lyttleton also meets with the same difficulties. In this theory he starts from a triple star. The two companions of the sun are supposed to form a very close binary. During the evolution of this binary system, they will draw closer to each other and finally the two stars will combine into one mass. This mass will, however, be rotationally unstable and will consequently break up. The result

WEIZSACKER—1945

Vortices formed in the equatorial plane of a nebula of gas and dust rotating about the sun, according to Weizsäcker. Accretion would take place along the heavy concentric circles, to form planets and satellite systems with direct rotation and revolution. Arrows indicate the direction of rotation.

of the fission of the combined mass will be that the two fission products will leave the system, leaving behind them a gaseous filament. The further development follows the same line as in Lyttleton's original theory.

According to another Cambridge astronomer, Hoyle, who has indicated a third possibility, starting from a binary system, a supernova outburst of the sun's companion may have resulted in the breaking up of the binary system and the production of a gaseous filament. From data concerning the Chinese supernova of 1054 A.D., which was presumably the origin of the Crab nebula, Hoyle concludes that this process might not be completely impossible. His theory, however, seems to encounter even more obstacles than Lyttleton's theories.[2]

[2] Spitzer has shown, for instance, that such a hot filament will disappear by evaporation before it can cool down sufficiently to allow condensation to take place.

Alfven's Theory

The Swedish physicist, Alfvén, has proposed a most interesting theory which takes into account the magnetic moment of the sun. This was previously done by the Norwegian scientist Birkeland, but he never followed up this idea by proposing a really detailed cosmogony.

Alfvén had two reasons for advancing this theory: (1) The magnetic force on charged matter due to the sun's magnetic field exceeds by far the gravitational force of the sun on the same matter in the regions of the solar system. (2) He had shown in an earlier paper that the rotating magnetic moment of the sun is able to cause currents in a neighboring ion cloud. Because of these currents the ion cloud will start to take part in the solar rotation, and the sun will be decelerated. In this way, an appreciable amount of angular moment can be transferred from the sun to such an ion cloud in a period of 10^5 years. This is short compared with the age of the solar system, which is of the order of magnitude of three billion years. The present distribution of the angular momentum is in this way easily explained.

Alfvén now proposes the following process for the formation of the outer planets: The sun is supposed to be surrounded, at a certain stage of its life, by an interstellar gas cloud. Due to the gravitational attraction of the sun, the atoms in the cloud will start falling toward the sun, and their kinetic energy will increase because of the gain of gravitational energy. Eventually, this energy will become so large that ionization through collisions will take place. Once an atom is ionized, the movement is arrested, and the ion has to move along the magnetic lines of force to an equilibrium position in the equatorial plane of the sun. In this way, Alfvén obtains a mass concentration in the equatorial plane. In this gaseous disc, condensation will take place, resulting in the formation of the planets.

This mechanism, though giving a possible solution for the formation of the outer planets, cannot account for the inner planets. The distance from the sun at which ionization occurs is too large to get any mass in the regions where the inner planets are observed. Alfvén suggests, therefore, without any detail, a different process for the formation of the terrestrial planets. He assumes that, at another stage of the sun's journey through space, it may have met an interstellar smoke cloud consisting of small solid particles. These particles will sublimate in the vicinity of the sun, the resulting atoms will become ionized, and a process similar to that described above will start, but at less distance from the sun.

A quantitative analysis of the processes discussed by Alfvén shows that they could never have played an important part in the formation of our solar system....

The Dust Cloud Hypothesis

Recently, Whipple has introduced an entirely new idea into this old problem. As yet, this idea has not developed into a theory, and it seems questionable whether this is possible.

Whipple starts from a cloud in which gas and smoke particles are mixed.[3] The contraction of this cloud, which has an original radius of about 30,000 A.U., should produce both the sun and the planets.

To account for the low angular momentum of the sun, the cloud is assumed to possess negligible angular momentum. The planets are assumed to be formed in a stream in the cloud. It is assumed that in this stream there are concentrations of matter which will ultimately produce the planets. Because the planets are formed in the stream, they will possess from the beginning the necessary angular momentum. On their path through the large cloud, these proto-planets will sweep up matter with zero angular momentum and consequently spiral inward.

The solution for the present distribution of the angular momentum is included in the theory from the beginning, so that this point presents no difficulties. The small eccentricities of the orbits are produced by the accretion process, as in the tidal theories of Jeans and Jeffreys. Whipple has not as yet studied the further development of these proto-planets closely enough to be able to explain any other properties of the system, and it seems extremely doubtful whether this will be possible.

A Revival of Kant's Theory

As is well known, the theory proposed in 1755 by Immanual Kant in his "Allgemeine Naturgeschichte und Theorie des Himmels," and given in a mathematical form by du Ligondès in 1897, was regarded as disproved because of the impossibility of understanding the present distribution of the angular momentum.

At present, however, it seems that this *communis opinio* was due to a misunderstanding of the problem, and quantitative calculations appear to show, to the contrary, that Kant's theory is probably the most promising of all existing theories.

[3] "Smoke particles" is a better name than dust particles for the solid particles existing in interstellar space, as was first remarked by van de Hulst following the nomenclature of physical chemistry, where smoke is the product of a condensation process.

The first author to start again from the same initial system as the one studied by Kant was the Dutch meteorologist, Berlage. He tried to combine Kant's and Laplace's theories by investigating the possibility of the formation of a system of rings in a gaseous disc surrounding the sun. From these rings the planets should have been formed by condensation in these rings, in Laplace's theory.

The second attempt was made by the German nuclear physicist, von Weizsäcker. His theory, which was dedicated to Sommerfeld on the occasion of his seventy-fifth birthday, will be discussed here in some detail, since von Weizsäcker draws attention to a few new features of the problem. Although his attempt seems also doomed to fail, his manner of attacking the problem can help us to explain many of the features of the planetary system.

First of all, von Weizsäcker shows that a gaseous envelope around the sun which possesses an angular momentum will assume a disc shape because of its rotation. The disc, however, is not stable. It can be shown that the velocities in the disc will follow Kepler's third law rather closely, *i.e.* the angular velocities decrease as the square root of the distance from the sun. Due to the differences of velocities, viscous forces will be present, striving to set up a rotation of a rigid body. The outer parts of the disc will thus be accelerated and move outward on account of the increased velocity, and the inner parts will be decelerated and move toward the sun in the center. Eventually, the disc will dissolve completely.

This dissipation of the disc is thus accompanied by three phenomena. First of all, the viscous stresses spend energy; this energy is provided by the matter falling onto the sun and gaining gravitational energy. Secondly, there is a transfer of angular momentum from the inner to the outer parts of the system. Thirdly, the matter of the system is dissipated, part of it falling on the sun, and the other part evaporating into space. . . .

The next step in von Weizsäcker's theory is the consideration of a pattern of vortices which might have existed in the disc. He shows that if we may assume that the orbits of the mass elements in the disc are unperturbed Keplerian ellipses, a regular system of vortices can be built up.[4] If the rotation of the disc is direct (counterclockwise), the movement in the vortices will be clockwise.

Von Weizsäcker considers this system for two reasons. First, gravitational forces are by far the most important forces in the disc, so that the orbits in the disc would be Keplerian if there were no collisions. Second-

[4] See diagram on p. 26.

ly, the energy dissipation will be less in a regular system such as that shown. The dissipation will take place along the circles where the rings of vortices meet. The viscous stresses along those circles, separating the main vortices, will give rise to secondary eddies. As can be shown, conditions for condensation will be more favorable in these "roller bearings," which means that we may expect the planets at distances from the sun, corresponding to the radii of these circles. In a system like that pictured, the ratio of the radii of two consecutive circles is constant, thus presenting us with the exponential Titius-Bode law....

During the formations of the planets they would be surrounded by an extended atmosphere. It is reasonable to assume that the formation of the satellite systems in these atmospheres would be analogous to the formation of the planets in the original gaseous disc.

Von Weizsäcker finally gives a qualitative picture of the condensation process, showing that the period necessary to build up bodies of the size of the planets is of the same order as the estimated lifetime of the disc.

Latest Developments

In view of the fact that none of the existing theories seemed to give a satisfactory solution, ter Haar tried to investigate in detail the properties of a gaseous, rotating solar envelope. A second reason for adding a new theory to the many which already exist was that no one had up to that moment given a *quantitative* analysis of the condensation process.

A short survey of this investigation will be given here, and it will be shown that by means of Kant's theory the differences between the inner and the outer planets may be explained.

As remarked above in the discussion of von Weizsäcker's theory, the explanation of the Titius-Bode law is still an open question. That point will not be discussed further here.

The first step in a quantitative analysis of Kant's theory ought to be a discussion of the physical and hydrodynamical aspects of the solar gaseous envelope, which will contain originally about one-half of the solar mass, and the density of which will be about 10^{-9} g cm^{-3}.

This analysis shows that the envelope will have a disc shape, *i.e.* the density decreases outward and in directions perpendicular to the equatorial plane of the sun. It also shows that ionization is negligible, and that the temperature in the disc will decrease as the inverse square root of the distance from the sun. At a distance corresponding to Mercury's mean distance from the sun the temperature will be about 400° C., de-

creasing to about —200° C. in the vicinity of Neptune. For the mean distance of the earth from the sun, we have about 130° C.

The hydrodynamical analysis enables us to calculate the rate of energy dissipation and, hence, the lifetime of the disc. Part of the matter in the disc falls on the sun, thus gaining gravitational energy: this process provides the energy lost in the dissipation process. The lifetime of the disc turns out to lie between 10^7 and 10^8 years. As we remarked before, the energy dissipation is a consequence of the viscous stresses in the disc, due to a velocity gradient corresponding to Kepler' third law. These viscous forces entail also a transfer of angular momentum. The inner parts of the disc will be slowed down. This process is analogous to the drag of a viscous fluid on a rotating disc, used to determine the viscosity coefficient....

Following analyis of the physical and hydrodynamical properties of the gaseous disc, the condensation process has to be considered quantitatively.[5] The condensation process can be divided into three phases: (1) the formation of nuclei for further condensation, (2) the growth of these nuclei, and (3) gravitational capture. The growth during the last stage is much faster than that during the first two stages.

Stages 1 and 2 are analogous to the formation of drops in a supersaturated vapor. From the theory of condensation it follows that the temperature determines which compounds are supersaturated at a given density. Whether or not a certain compound is supersaturated at a given temperature and density depends on its heat of sublimation. If the heat of sublimation is larger than a critical value, the compound will be supersaturated, otherwise not. The critical heat of sublimation is mainly determined by the temperature and depends only slightly on the density.

In the gaseous disc, the temperature decreases with increasing distance from the center. Consequently, in the regions nearer to the sun fewer compounds will take part in the initial condensation phases than in the outer regions of the solar system. It now turns out that, in the regions of the solar system where the terrestrial planets are found, only inorganic compounds will condense. In the regions of the outer planets, however, both organic and inorganic compounds can condense. It is very remarkable that the change-over from inorganic to organic compounds lies just in the region between the inner and outer planets.

[5] We may remark here that in the planetesimal theory of Chamberlin and Moulton similar considerations were given, though those authors did not discuss the processes very extensively and quantitatively.

This has two consequences. First of all, there will be fewer condensation nuclei in the inner parts of the system than in the outer parts. Secondly, the specific density of the condensation nuclei in the inner regions will be higher than that of the nuclei in the outer regions. From this alone, we could already expect heavier, small inner planets and light, large outer planets.

This precipitation of the supersaturated compounds will continue until the bodies have become so large that gravitational effects will become important. The gas molecules are then captured in the gravitational fields of the condensation products, and the proto-planets will grow very fast until the gas is exhausted.

The bodies for which gravitational capture begins to play a role are of about the same size as Venus. From this, we see that this last stage has not been important in the building-up process of the inner planets. For the outer planets, however, gravitational capture has been important, thus increasing their mass and decreasing their specific density because of the capture of the light compounds which were not supersaturated even at temperatures of about —200° C.

The reason why the outer planets have grown beyond the second stage, and the inner planets not, is that the lifetime of the disc is of the same order of magnitude as the time necessary to reach the stage of gravitational capture. The inner planets grow more slowly than the outer planets during the first two stages because fewer compounds play a part in these stages. Therefore, the outer planets may well have reached the third stage before the dissipation of the disc became important, but when the inner planets had attained that size, the dissipation of the disc prevented an appreciable further growth.

It is possible to explain even the small differences in density of the various planets. Brown has shown that, if one assumes that all the inner planets are built up from the same material, their densities will vary because of a variation of pressure in their interior, due to their varying masses. As for the outer planets, we have to assume that they are built up of heavier material plus some lighter gases captured during the last stage of their formation. In that way the differences in density can all be understood.

We will assume now that in the building up of the outer planets about twenty times as much of the matter in the disc has taken part as in the formation of the inner planets, corresponding to the fact that for the outer planets gravitational capture has been important. We can then esti-

mate the masses of the planets if they should have been formed in the disc at their present distances from the sun.

In Table 1 we have inserted the values of the planetary masses, calculated under this assumption. The masses are expressed in the earth's mass as unit.

TABLE 1

Planet	Observed Mass	Calculated Mass
Mercury	0.05	0.1
Venus	0.8	0.5
Earth	1	1
Mars	0.1	2
Jupiter	318	130
Saturn	95	90
Uranus	15	20
Neptune	17	3
Pluto	0.9	0.8

The agreement between the calculated and the observed masses seems to be quite good.

In order to get sufficient mass to build up bodies of the size of the present planets, it appears that the original solar envelope must have contained between one- and five-tenths of the solar mass, because only part of the matter can take part in the condensation process.

During their formation, the outer planets would be surrounded by extended atmospheres. The evolution of these atmospheres will probably be analogous to the evolution of the solar envelope. In this way we have a mechanism for the formation of the satellite systems. Since these atmospheres will be large for the outer planets, and practically absent for the inner planets, we can readily understand why the outer planets are surrounded by extensive satellite systems while the inner planets possess only a few satellites....

In conclusion, it seems that Kant's theory is stronger than was suspected for a long time. This is rather satisfying, since Kant's theory starts from probably the simplest possible hypothesis—a sun, surrounded by a gaseous envelope.

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